

Energy analysis of a novel domestic scale integrated wooden pellet-fueled micro-cogeneration concept

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ABSTRACT

In this paper, the feasibility of conceptual 1.9 kW_e micro-cogeneration technologies is evaluated by way of annual energy balances and weighted energy matching indices (WMI). The concept is based on a commercial 20 kW_{th} wooden-pellet fueled boiler, in which a rotary steam engine (RSE), a Stirling engine (SE) or a domestic thermoelectric cogeneration system (DTCS) can be easily integrated. Both thermal and electrical tracking strategies are examined with an option to charge an electric car and to deliver surplus heat to a local thermal grid. The sizing of electrical and thermal storages is discussed. The hourly energy demands are simulated using the whole-building simulation tool IDA-ICE for detached houses representing two energy performance levels and located in three climatic zones in Finland. The performance of micro-cogeneration is assessed through electrical and thermal efficiencies obtained from recently published performance analyses. The results indicate that by using the suggested concept, the energy demands of the case building can be met in cold climates and a good energy match can be obtained. The energy match can be improved slightly by using an electrical storage of maximum 100 A h (4.8 kW h) or a thermal storage of maximum 1500 L (17.5 kW h).

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1. Introduction

The most common domestic scale micro-cogeneration technologies within the power range of 0–2 kW_e are fuel cells (FC), Stirling engines (SE), Organic Rankine Cycle (ORC) and internal combustion engines (ICE), the most common nominal electrical power being 1 kW_e in commercial products [1]. In practice, the internal combustion engine (ICE) is the only time-tested technology with an established market [2]. About 30,000 micro-CHP units based on 5 kW_e ICE's have been installed in Germany in the recent years [3]. Average thermal efficiencies of 76% and electrical efficiencies of around 12% have been achieved. With the fuel cells, a high electrical efficiency (up to 40% LHV) and a favorable electrical to thermal ratio (ETTR) (up to 0.59) can be obtained [1]. However, the market is restrained by the emerging market status of fuel cell technology. The need of fuel processing (e.g. gasification, reformation or electrolysis) can be regarded as a disadvantage in terms of market development. Stirling engines (SE) raise to the challenge with their ability to utilize a variety of thermal sources. The technology is still emerging, but widely cited in the context of domestic scale micro-cogeneration [4].

Requirements related to flexible thermal sources, efficiency, operational temperatures, controllability, noise, space requirement and capital cost have increased the willingness to introduce new micro-cogeneration technologies. According to Dong et al. [5], the market potential of biomass-fueled micro-cogeneration technology has been recognized worldwide, but the level of its commercialization and implementation is still low. Bonnet et al. [6] suggest the Ericsson engine as an alternative to SE due to its less complicated design and thus potentially reduced costs. Organic Rankine Cycle (ORC) has been considered a promising, low-cost alternative for biomass-fueled micro-cogeneration, capable of operating at low temperatures, which makes it suitable for waste heat recovery [7].

A rotary steam engine (RSE) is an oil-free medium-speed (1000–2000 rpm) engine. It is capable of exploiting versatile thermal sources and steam temperatures of 150 to 180 °C, which allow operational pressures less than 10 bar for electrical power ranges of 1–20 kW_e. The concept would be simple, small and quiet option for micro-cogeneration. An RSE can be easily integrated in commercially available biomass-fired household boilers. Alanne et al. [8] conceptualized an RSE to be integrated with a commercial pellet-fueled boiler and modeled and analyzed the performance of the system.

A domestic thermoelectric cogeneration system (DTCS) is a noiseless and maintenance-free method of on-site

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Nomenclature

AC	alternating current
ACH	air change rate [1/h]
AMI	averaged matching index [–]
CHP	combined heat and power
DC	direct current
DHW	domestic hot water
DTCS	domestic thermoelectric cogeneration system
E_{el}	annual electrical energy [kW h/y]
E_{fuel}	annual fuel energy (LHV) [kW h/y]
E_{th}	annual thermal energy [kW h/y]
ES	net electrical power sent to electrical storage [kW]
ETTR	electrical to thermal ratio [–]
F_{dh}	thermal power imported/exported from the grid [kW]
F_{eg}	electrical power imported/exported from the grid [kW]
F_{fuel}	fuel input (LHV) to the micro-cogeneration system [kW]
FC	fuel cell
FSOC	fractional state of charge [–]
G_e	electrical power generated by the micro-cogeneration system [kW]
G_{th}	utilizable heat generated by the micro-cogeneration system [kW]
HS	net thermal power sent to heat storage [kW]
HVAC	heating, ventilation and air-conditioning
ICE	internal combustion engine/indoor climate and energy
L_{elec}	electrical demand [kW]
L_{heat}	heat demand [kW]
l_e	electrical losses of power distribution system [kW]
l_{th}	thermal losses of heat distribution system [kW]
LHV	lower heating value
MCHP	micro-scale combined heat and power
OEF _e	on-site electrical energy fraction [–]
OEF _h	on-site thermal energy fraction [–]
OEM _e	on-site electrical energy matching index [–]
OEF _h	on-site thermal energy matching index [–]
ORC	organic Rankine Cycle
RSE	rotary steam engine
SE	Stirling engine
SFP	specific fan power [kW/m ³ /s]
t	time [h]
t_{op}	annual operational hours [h/y]
ULE	ultra low-energy house
WMI	weighted matching index [–]
η_a	annual efficiency [%]
η_e	electrical efficiency [%]
η_{ES}	electrical storage efficiency [%]
η_{th}	thermal efficiency [%]
η_{tot}	overall efficiency [%]

micro-cogeneration, with no moving parts. Zheng et al. [9] developed a bench-scale experimental prototype of a DTCS to be integrated in a domestic boiler system. Their target was to improve the electrical efficiency by better organizing the heat transfer and to avoid the use of a cooling fan, which was mentioned as a disadvantage in the stove applications. Their study did not address the boiler operation according to the user's needs and boiler size. Alanne et al. [10] characterized and analyzed a concept where thermoelectric modules were directly integrated in the combustion chamber and convection tubes of a commercial

wooden-pellet fueled boiler, to keep structural changes minimal and the temperature difference large.

The need for energy matching originates from the legislative challenge to meet the objective of nearly-net-zero-energy buildings by compensating the energy imported from the grids [11]. To assess the energy matching of individual buildings employing various on-site micro-cogeneration technologies, Cao et al. [12] suggested four energy matching indices. Two on-site energy fractions (OEF_e and OEF_h) indicate the proportion of the load covered by on-site generated electricity and heat, whereas the on-site energy matching indices (OEM_e and OEM_h) determine the proportion of on-site generated electricity and heat used in the load instead of dumping or exporting it. The index numbers vary between zero and unity and the higher the value is, the better is the applicability of the system in the examined building. With micro-cogeneration technologies, the averaged matching index AMI = 0.85 was acquired as a baseline of good matching, when an electrical storage is not used, and AMI = 0.75, when it is present [12].

The earlier work of Alanne et al. [8,10] focused on assessing the saving potentials of the two new micro-cogeneration concepts in primary energy, carbon dioxide emissions and annual energy costs. Instead, they neglected assessing the impact of the building's energy performance level, electrical and thermal grid feed-in options, size of the on-site electrical storage, and energy matching. In the present study, the performance of the above micro-cogeneration systems are analyzed for two energy performance levels and three electrical demand profiles in three climatic zones in Finland.

2. Calculation

2.1. Target building

The target building is a one-floor single-family house with the heated area of 134.3 m². The house is equipped with a mechanical ventilation system and the heating system is programmed to maintain a room temperature of 21 °C. No cooling system is present, which allows the temperature to rise during summer months. The blueprint and a 3D model of the building are shown in Fig. 1.

Two energy performance levels are applied in the present study. The “1960 house” is represented by the default values of overall thermal transmittances (*U*-values), the level of air tightness of the envelope, and the specific fan powers (SFP) of the ventilation system defined for the detached houses built before 1969 in [13]. Correspondingly, the second level, the “ultra low-energy house” (ULE) makes use of the Finnish guidelines for the ultra low energy houses, defined in [14]. The air change rate (ACH) for the “1960 house” is based on the average air exchange rate of the houses with mechanical exhaust ventilation system, reported in [15]. For the “ULE”, the guideline of the Finnish building code [16] is followed. The “1960 house” is equipped with a central mechanical exhaust ventilation system and the “ULE” is equipped with supply and exhaust ventilation with heat recovery. The net heat demand of domestic hot water is based on the default value of Finnish building code D3 [17] and the annual efficiencies of domestic hot water (DHW) distribution (non insulated pipes: 0.75 and well insulated pipes: 0.92) are based on the default values of Finnish building code D5 [18]. The key building parameters are summarized in Table 1.

2.2. Electrical demand profiles

2.2.1. Lighting and appliances

The total electrical demand is the sum of the power requirements of appliances (including fans and pumps) and lighting. The annual level of electrical consumption for appliances

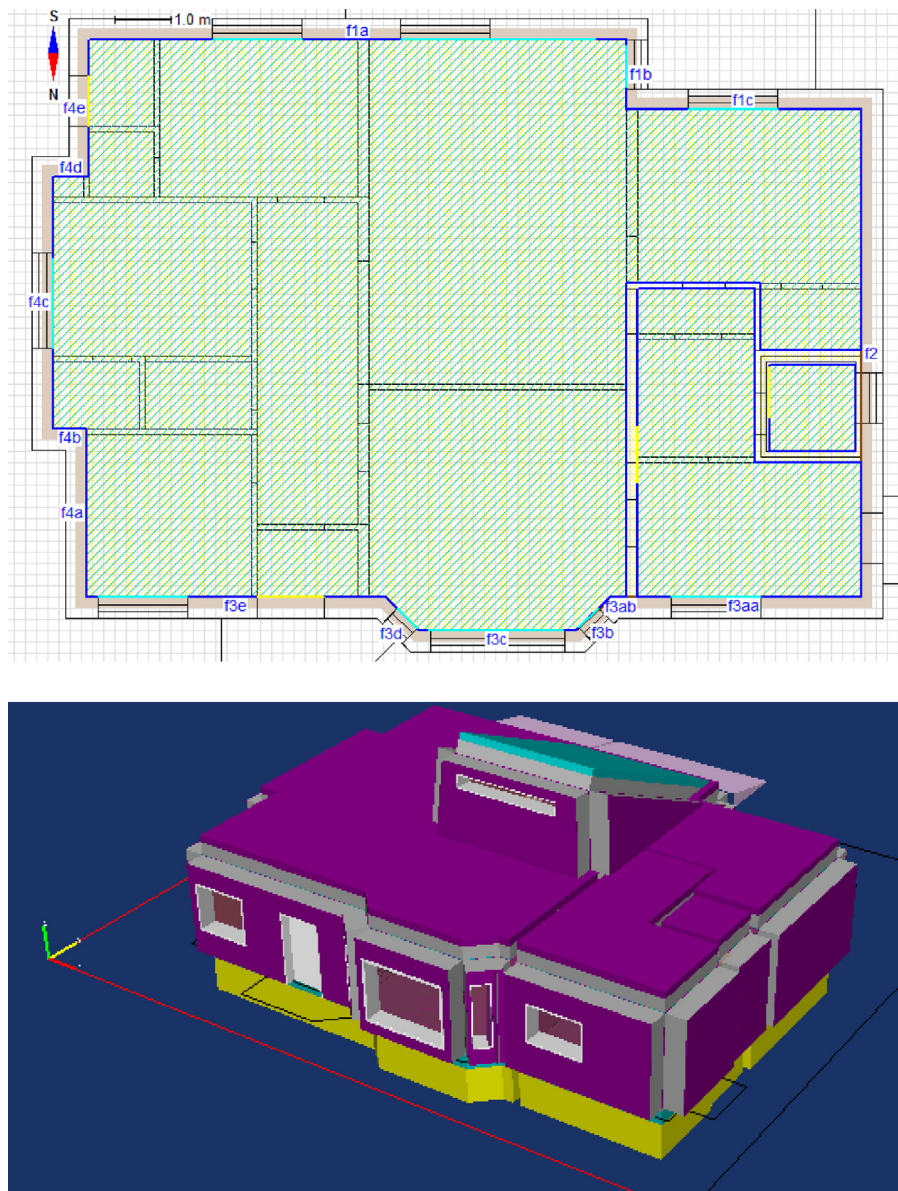


Fig. 1. Geometry of the target building.

(HVAC excluded) according to the Finnish Building Code D3 ($15.8 \text{ kW h/m}^2, \text{y}$) is divided for each hour of the day on the basis of everyday experience. For lighting, the corresponding annual consumption ($7.2 \text{ kW h/m}^2, \text{y}$) is divided seasonally for spring (March 15 to April 30), summer (May 1 to July 31), autumn (August 1 to October 14) and winter (October 15 to March 14). The electrical demand of HVAC fans is calculated according to the SFPs. The same electrical demand profile is applied to both energy performance levels. The daily profiles are shown in Fig. 2. The lighting profiles vary depending on the location. The profile in Fig. 2 represents Helsinki conditions.

2.2.2. Charging electric car

Charging electric cars (e-cars) is evaluated by assuming one electric car per household, which is to be re-charged during the time range from 6:00 PM and 7:00 AM. This is in line with the work of Robinson et al. [19], who observed that the peak re-charging is situated between 6:00 PM and midnight, whereas at 6:00 AM the frequency of re-charging among private users is nearly zero. Similar perceptions have been also published in [20]. On the basis of

everyday experience, the daily mileage is chosen 40 km, representing commuting traffic in an average Finnish urban area. The car is represented by Elcat Cityvan, which consumes 24 kW h per 100 km according to the manufacturer's notification. The nominal battery capacity is 23 kW h and the battery can be charged from 0% to 90% in 5 h and from 0% to 100% in 9 h. Measurements during one week in November 2013 indicated that 76% of the electrical power drawn from the grid (3.4 kW in average, fuse: at least 16 A) can be stored in the battery. The rest (24%) is forfeited due to power management losses and warming up the battery.

2.3. Micro-cogeneration plant

The suggested micro-cogeneration concept is based on a commercial pellet-fueled hydronic boiler (Ariterm Biomatic 20+) with nominal thermal output of 20 kW_{th} . The standard boiler's combustion chamber is made of steel or another metal with a good thermal conductance and tolerance for high temperatures. The combustion chamber is surrounded by a body of circulated water. The temperature of exhaust gases drops significantly, before the gas exits

Table 1
Summary of the key building parameters.

Properties	Energy performance levels	
	1960 House	ULE
Location (Design outdoor temp.)	Design heating power (spaces + ventilation) (kW)	
Helsinki (−26 °C)	18.6	5.8
Jyväskylä (−32 °C)	21.8	6.7
Sodankylä (−38 °C)	24.7	7.8
U-values (W/m ² K)		
Ext wall	0.81	0.08
Roof	0.47	0.07
Base floor	0.47	0.1
Doors	2.2	0.5
Windows (frames and glazing)	2.8	0.8
Window properties		
Solar factor (g-value)	0.78	0.46
Solar transmittance	0.74	0.39
Visible transmittance	0.82	0.64
Air tightness		
n ₅₀ -Value (1/h)	6	0.5
Ventilation		
Ventilation rate, ach	0.36	0.5
Eff. of heat recovery (%)	n.a.	85
Min leaving air temperature (°C)	n.a.	−1
SFP (kW/m ³ /s)	1.5	1.4
Heat distribution of space heating	Radiators (70/40 °C)	Floor heating (40/30 °C)
DHW		
Net heat demand (kW h/m ² .y)	35	35
Annual efficiency of distribution	0.75	0.92
Mechanical cooling	No	No

from the combustion chamber. The remaining heat of exhaust gases is recovered in convection tubes after the chamber. The water is circulated and it can be stirred, which enables intensified forced convection from the outer surface of the combustion chamber to water. The boiler entails a hot water storage, the temperature of which is kept between lower and upper boundaries (80–90 °C) by the ON–OFF control of the burner. The performance of the boiler has been tested following the European Standard EN 303-5, Clause 4.1 by the Technical Research Centre of Finland (VTT). The data on the boiler and the fuel is summarized in Table 2.

In the first option of micro-cogeneration, the evaporator of the rotary steam engine (RSE) is built in the boiler's combustion chamber. The return water from the radiator network is circulated through the condenser into the water tank of the boiler. The condenser can be located in the circulation before or after the water tank, or inside the tank. The burner is still ON–OFF controlled. When the burner is fired up, the RSE process is pressurized and the

Table 2
Boiler data.

Net weight (empty) [kg]	245
Gross (installed) dimensions [mm]	935 × 608 × 1755
Heat transfer area of combustion chamber [m ²]	0.72
Heat transfer area of convection tubes [m ²]	1.35
Water volume [L]	140
Measured boiler efficiency (LHV) at nominal thermal load [%]	91%
Measured boiler efficiency (LHV) at 30% thermal load [%]	86%
Pellet diameter [mm]	8
Moisture content [%]	8.6%
Calorific value [MJ/kg]	17.25

electricity generation starts. The rest of the heat is transferred into the water envelope. A pump circulates water from the condenser to the evaporator, taking its power from the shaft of the RSE. A Stirling Engine (SE) can be integrated into the standard boiler in a way resembling the integration of the RSE [8]. The condenser and the evaporator are now substituted by gas-to-gas heat exchangers, helium acting as the working gas. A schematic diagram of this concept is illustrated in Fig. 3.

The physical body of the domestic thermoelectric cogeneration system (DTCS) is identical with the standard boiler, but the combustion chamber and the convection tubes (which are made of 5 mm steel plate in the standard boiler) are now replaced by thermoelectric structure, which consists of N and P type semiconductors (thermoelectric materials). The combustion chamber can be either coated with thermoelectric modules or designed so that the heat transfer surface itself builds up one single water-proof thermoelectric structure. Here, the thermoelectric structure works as insulator, and a multi-layered element is used to ensure as large temperature difference as possible (to allow maximum voltage). Exhaust gases exit from the combustion chamber at higher temperature, and a major part of the heat transfer now takes place in convection tubes after the chamber. The concept is illustrated in Fig. 4.

According to Alanne et al. [8], an RSE micro-cogeneration plant is capable of obtaining the net electrical efficiency of 9% (based on the lower heating value of the fuel, LHV) and the thermal efficiency 77% (LHV) in the design temperature of 150 °C, which results in an electrical output of 1.87 kW_e, and the utilizable thermal output of 16.5 kW_{th} with the fuel input of 21.45 kW (the nominal fuel input of the standard boiler). The present application is accommodated to the design pressure of 4.76 bar, which allows the system to be operated by a customer without periodic inspection of pressure devices according to the Finnish law 869/1999 for pressure vessels [8].

If the above concept was realized through Stirling Engine micro-cogeneration instead of an RSE, the electrical, thermal and overall efficiencies of 7.3%, 71%, and 78.3% would be obtained, resulting in the nominal output of 1.58 kW_e/15.2 kW_{th} with the fuel input of 21.45 kW. The performance of the SE boiler remains inferior to that of the corresponding RSE system due to the limited physical size of the boiler. Here, the design of the heat exchanger is not optimal and the heat transfer is less effective.

The results reported by Alanne et al. [10] suggested that the theoretical electrical output of the domestic thermoelectric cogeneration system (DTCS) is 1.9 kW_e, and the electrical plant efficiency of 8.9% (LHV) can be obtained, when the figure of merit of the thermoelectric material is unity and the thickness of the structure 40 mm. Here, temperature differences up to 660 °C can be achieved with the proposed configuration, the hot side temperature reaching the level of 750 °C (1023 K). A power management unit (sine wave inverter) is required to convert the DC output to alternating current (AC) at desired voltage level (e.g. 220 V) and frequency (e.g. 50 Hz), which slightly drops the electrical efficiency in practical applications.

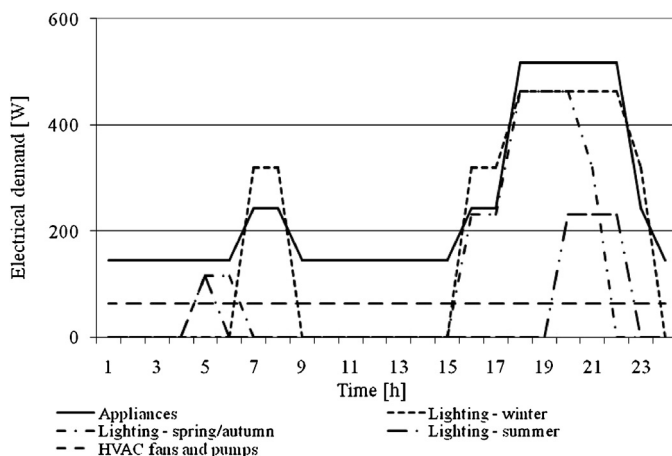


Fig. 2. Daily electrical demand profiles.

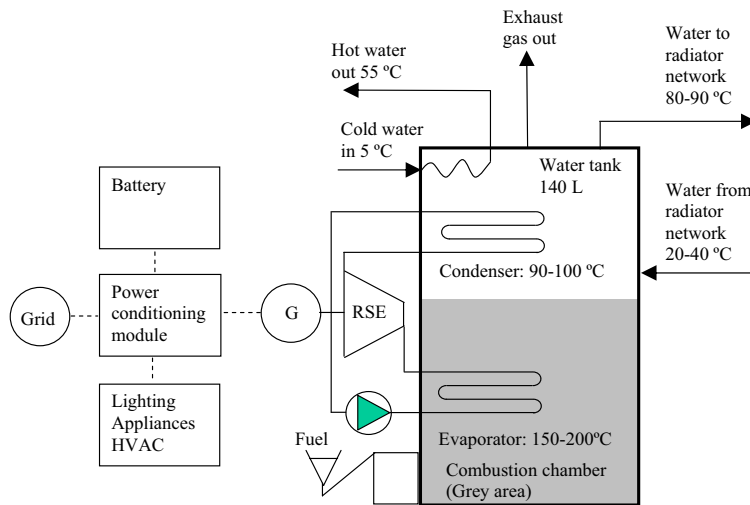


Fig. 3. A schematic diagram of the RSE micro-cogeneration concept [8].

The reader is referred to Alanne et al. [8,10] for further details related to the micro-cogeneration options suggested above.

2.4. Operational strategies

In the boiler system, the temperature of the supply water for the radiator network is controlled by mixing the return water from the radiator network with the hot storage tank water, where the set point for the supply water temperature (max. 70 °C) is determined on the basis of outdoor temperature. Domestic hot water (55 °C) is also produced in the boiler, by circulating cold water (5 °C) through a heat exchanger located in the top of the hot water storage tank (80–90 °C) [21]. The electrical demands of circulation pumps are calculated inside the energy balance of the building (not that of the boiler system).

In the present study, two operational strategies are examined. In the thermal tracking mode, the heat generation follows the thermal demand of the building. The burner is switched off, when the temperature in the top of the storage tank exceeds the upper limit (90 °C) and it is switched on, when the temperature undercuts the lower limit (80 °C). When the net generated electricity surpasses the momentary electrical demand, it will first charge a battery. Here, the battery voltage is taken as 48 V and its capacity may vary

between zero (no battery) and 200 A h, which equals to 9.6 kWh. The fractional state of the charge (FSOC) is kept between 0.3 and 0.9, as in [12]. If the battery capacity is exceeded and there is still surplus of electricity, it will be fed into the power grid through an appropriate power conditioning system at the required AC/DC voltage. If the electric car is present and needs re-charging, the batteries of the electric car are charged first and the momentary electrical demand is increased by the power demand of the charging system. It would be also possible to discharge the batteries of an electric car to meet the electrical demand of the building, but the availability of this option is limited at the moment and therefore it has not been examined in the present study.

In the electrical tracking mode, the power generation follows the electrical demand of the building. Electricity is drawn from the grid, if the local demand cannot be met by on-site generation and discharging the battery. Here, the key requirement is that the water storage temperature can be kept between the given lower and upper limits in all conditions. Hence, an extra heat exchanger is needed in the top of the storage tank to export or deliver heat to or from external heat storage, thermal grid or another external heat sink (e.g. swimming pool). Due to limited space in the water tank of the boiler (140 L), large heat transfer surfaces cannot be mounted. Therefore, sufficient heat transfer must be ensured by a sufficient temperature difference between the boiler and the external thermal storage and a large enough mass flow of the water circulation.

In the Finnish district heating system, the common design temperatures (winter conditions) for the heat exchangers are 115 °C for the supply water and 45...65 °C for the return water of the district heating [21]. For the summer conditions, (domestic hot water only), the design temperature is 70 °C. Schubert [22] implies that the most suitable heat grid feed-in technology in this context might be “Feed-in return → return”, i.e. connecting the micro-cogeneration with the return flow of the heat grid, allowing the lowest operational temperatures. Since the temperature of the water tank must be kept between 80 and 90 °C and thermal shortage in winter cannot be avoided in electrical tracking mode, the system should have a separate heat exchanger connected to the supply line of the district heating system, as well. The requirement of additional heat exchangers would apparently reduce the economic attractiveness of the thermal grid option. On the other hand, feeding the thermal output of a micro-cogeneration system to the return line of the grid would result in reduced overall system performance through higher temperature and greater losses, which would make the option unfavorable in terms of energy efficiency.

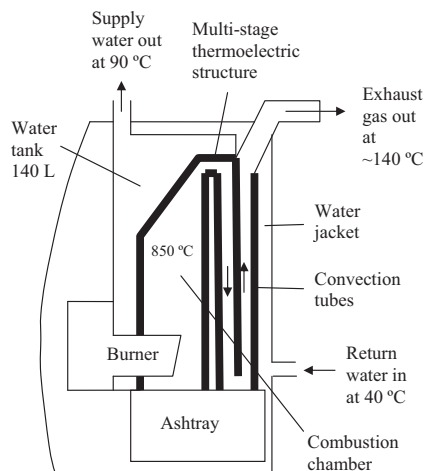


Fig. 4. Installation of domestic thermoelectric cogeneration in the standard boiler [10].

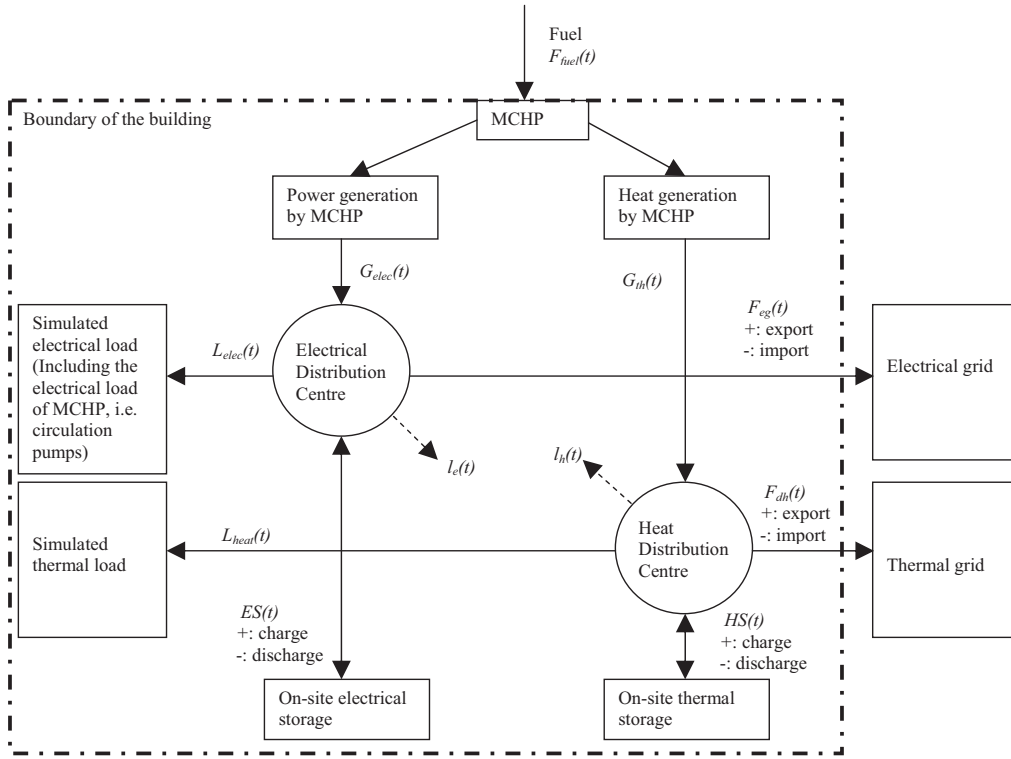


Fig. 5. Simplified topology of energy matching analysis adapted from [12].

Drawing further conclusions on to which extent a thermal grid would allow excess heat to be exported, however, would require detailed modeling of the thermal grid system and sizing of the heat exchangers. For the sake of simplicity, the assumption has been made here that the excess heat can be fed into the thermal grid provided that the grid option is available. The shortage of thermal power at the required temperature level could be also compensated by installing electrical resistance in the hot water tank, but this option is neglected, because electricity is appreciated as a “high-value” form of energy and converting it into heat would result in undesired exergy loss.

2.5. Methodology

Adapting the simplified topology described by Cao et al. [12], the micro-cogeneration system is modeled by way of two energy distribution nodes, namely, (i) electrical distribution centre and (ii) heat distribution centre. All the imported and exported thermal and electrical powers to, from and inside the boundary of the building are delivered through these distribution centers as illustrated in Fig. 5.

The energy balances for both the electrical and heat distribution centers must be fulfilled for each moment of time and they can be written as:

$$G_{elec}(t) - L_{elec}(t) - I_e(t) \pm F_{eg}(t) \pm ES(t) = 0 \quad (1)$$

$$G_{th}(t) - L_{heat}(t) - I_h(t) \pm F_{th}(t) \pm HS(t) = 0 \quad (2)$$

At a given time range, the ON/OFF-controlled micro-cogeneration (MCHP) system operates as long as is needed to fulfill the net thermal (or electrical) energy demand of that time range. The performance of the integrated system is characterized

in terms of electrical, thermal and overall efficiencies defined in Eqs. (3)–(5):

$$\text{electrical efficiency } \eta_e = \frac{G_{elec}(t)}{F_{fuel}(t)} \quad (3)$$

$$\text{thermal efficiency } \eta_{th} = \frac{G_{th}(t)}{F_{fuel}(t)} \quad (4)$$

$$\text{overall efficiency } \eta_{tot} = \frac{G_{elec}(t) + G_{th}(t)}{F_{fuel}(t)} \quad (5)$$

In the above definitions, F_{fuel} is the fuel input calculated on the basis of lower heating value (LHV), G_{th} is the thermal flow delivered to the water circulation, and G_{elec} is the net electrical power in AC.

In the present application, the electrical demands of HVAC fans and pumps, distribution heat losses and the skin losses of the boiler unit have been dealt with in the building simulation model (IDA-ICE). Instead, the power demand of the circulation pump of the micro-cogeneration system as well as its electricity conversion losses has been taken into account in the electrical efficiency and the losses through exhaust gases in the thermal efficiency.

Losses related to on-site electrical storage are estimated through post-processing the simulation results. Only a certain fraction of electrical energy demand of the battery charger can be later discharged and utilized. This fraction is defined as the electrical storage efficiency:

$$\eta_{ES} = \frac{ES^-(t)}{ES^+(t)} \quad (6)$$

where ES^- is the utilizable electrical power that can be discharged from electrical storage and ES^+ is the electrical power sent to the electrical storage.

In the thermal tracking mode, high temperature is maintained in the water tank outside the heating periods, too, because the boiler must be kept stand by for hot water production. This, in turn, results in extra fuel consumption (idling loss), which has to be taken into account for the energy analysis. Alanne et al. [8] estimated that

at the boiler envelope temperature of 40 °C (313 K) and the surrounding temperature 25 °C (298 K), the overall heat flow due to skin losses would be 283 W (= free convection from the vertical surfaces and the top of the boiler, the lower surface being insulated). Here, this 283 W is assumed to represent the loss during the hours, when the thermal demand is zero, but the boiler must be kept warm (varies depending on the energy performance level of the building).

Due to the idling loss, the annual efficiency remains inferior to the overall efficiency defined in Eq. (5). The annual efficiency during the time period $t_1 \dots t_2$ is defined as:

$$\eta_a = \frac{\int_{t_1}^{t_2} [L_{elec}(t) \pm F_{eg}(t) + L_{heat}(t) \pm F_{dh}(t)] dt}{\int_{t_1}^{t_2} [F_{fuel}(t)] dt} \quad (7)$$

The energy matching indices are defined as follows [11]:

$$OEFe = \frac{\int_{t_1}^{t_2} \min[G_{elec}(t) - ES(t); L_{elec}(t)] dt}{\int_{t_1}^{t_2} [L_{elec}(t)] dt}, \quad 0 \leq OEFe \leq 1 \quad (8)$$

$$OEFh = \frac{\int_{t_1}^{t_2} \min[G_{th}(t) - HS(t); L_{heat}(t)] dt}{\int_{t_1}^{t_2} [L_{heat}(t)] dt}, \quad 0 \leq OEFh \leq 1 \quad (9)$$

$$OEme = \frac{\int_{t_1}^{t_2} \min[G_{elec}(t); L_{elec}(t) + ES(t)] dt}{\int_{t_1}^{t_2} [G_{elec}(t)] dt}, \quad 0 \leq OEme \leq 1 \quad (10)$$

$$OEmh = \frac{\int_{t_1}^{t_2} \min[G_{th}(t); L_{heat}(t) + HS(t)] dt}{\int_{t_1}^{t_2} [G_{th}(t)] dt}, \quad 0 \leq OEmh \leq 1 \quad (11)$$

To simplify the technology assessment when several technologies are to be evaluated, Cao et al. [12] recommend that the four separate indices should be reduced into a single number through a weighted matching index (WMI), i.e. the weighted average of OEme, OEmh, OEFe and OEFh. Eliciting the weight factors is challenging due to the evaluators' subjective preferences. Therefore, weight factors should be assigned on the basis of jointly approved criteria. For example, the maximum proportion of on-site electricity could be particularly preferred by the policy makers due to socio-economic or environmental reasons. A further limitation of the above approach is according to [12], that the overall matching index provides a “macroscopic” perspective on the matching

Table 3

Energy consumptions by energy efficiency standard and climate.

Location (energy performance level)	Heat [kW h/y]	Electricity [kW h/y]	e-Car [kW h/y]
Helsinki (1960 house)	40,320	3648	5110
Jyväskylä (1960 house)	45,920	3648	5110
Sodankylä (1960 house)	55,057	3642	5110
Helsinki (ULE)	10,540	3723	5110
Jyväskylä (ULE)	11,727	3723	5110
Sodankylä (ULE)	14,215	3717	5110

capabilities. On the other hand, the computational modeling of conceptual micro-cogeneration systems does not give an accurate, but an indicative image on how the commercial micro-cogeneration plants would behave in realistic operating conditions.

3. Results and discussion

3.1. Energy balances

The energy performance of the target building was investigated in three locations in Finland: Helsinki, Jyväskylä and Sodankylä. The hourly demands profiles (hourly average power) were calculated for two energy performance levels (1960 house and ULE) and each climate using the IDA-ICE whole-building simulation tool, which has been validated, for example, in Traversi et al. [23] and Loutzenhiser et al. [24]. In validity tests, the variation between actual energy demand and energy demand estimated on the basis of dynamic, whole-building simulations has been observed to be up to $\pm 10\%$, but the best agreements lay within $\pm 3\%$ [25]. The annual net energy consumptions are summarized in Table 3 and the duration of thermal and electrical power (Helsinki, Jyväskylä) is shown in Fig. 6. The electrical demand profile in Sodankylä is slightly different due to lighting, but it has been omitted, since the difference would be hard to perceive from the graph.

The energy balances, annual efficiencies (η_a) and operational hours (t_{op}) were calculated for each micro-cogeneration concept and control strategy in each climate and energy performance level. The system contains the electrical storage capacity of 4.8 kWh and efficiency of 90%. The DTCS is represented by the optimum electrical efficiency and the structure thickness of 40 mm. Since the micro-cogeneration concepts are identical to the standard boiler system in the sense of heat distribution, the simulated net energy demand also applies to the cases with micro-cogeneration.

Tables 4 and 5 summarize the findings in the thermal tracking mode for the 1960 house and the ULE. Here, E_{el} , is the annual electrical energy (kW h/y), the minus sign representing the annual shortage and the plus sign surplus. In thermal tracking mode, the net thermal energy demand is completely (100%) fulfilled on-site, but the percentage of on-site electricity varies. The “on-site-%” indicates the fraction of net energy demand generated on-site in the total annual net energy demand. For example, the Stirling engine micro-cogeneration concept generates 2969 kW h/y (of 3648 kW h/y) in Helsinki in the 1960 house, the “on-site-%” being 81%.

Because the boiler with integrated Stirling engine operates at a low efficiency, the operational hours and the annual fuel consumption (E_{fuel}) are increased in comparison with the RSE and DTCS. The performances of the RSE and DTCS are almost identical. When the electric car is present, the proportion of on-site energy is cut to half and the annual grid electricity is approximately tenfold (1960 house). In the case of the ULE, the boiler operates only about 25% of the operational hours in the 1960 case. Therefore, the proportion of on-site electricity decreases drastically, no electrical surplus occurs and most of the annual electricity must be delivered from the grid.

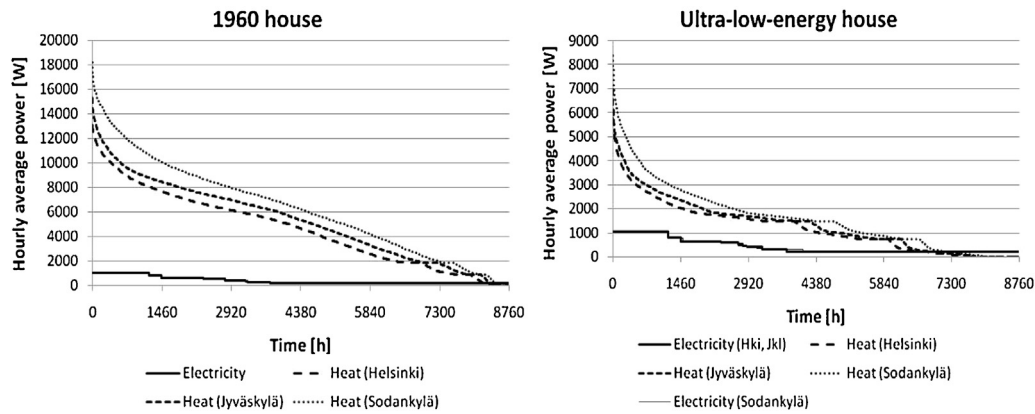


Fig. 6. Duration curves for the electrical and thermal power (no e-car present).

Tables 6 and 7 summarize the findings in the electrical tracking mode. Here, E_{th} , is the annual thermal energy (kWh/y), the minus sign representing shortage and the plus sign surplus. The net electrical energy demand is completely (100%) fulfilled on-site, whereas the percentage of on-site thermal energy varies. Almost 50% of the annual thermal demand can be fulfilled in all the examined cases. On the other hand, there is no condition where the electrical tracking mode would not result in a significant annual thermal surplus. Hence, all the investigated pellet-fueled micro-cogeneration options would require either a connection with a thermal grid or another local thermal management or storage option.

Since the ETTR of the Stirling engine is the lowest (0.1), it is capable of covering slightly greater percentage of the total thermal demand in the electrical tracking mode than the RSE and DTCS, however, with the cost of increased fuel consumption. Here, electrical car is not counted into the “on-site” electricity use, wherefore it does not affect the on-site percentages. In the electrical tracking mode, the micro-cogeneration concepts are capable of generating approximately 50% of the required electricity when an e-car is present. In that case, the number of operational hours is increased by 27% in Helsinki and by 42% in Sodankylä in comparison to the case with no e-car. Because there is no significant difference

between the electrical demand profiles of the 1960 house and the ULE, the number of annual operational hours is approximately the same in both cases, and the difference appears in thermal shortage and surplus only. Some thermal shortage cannot be avoided in the electrical tracking mode in the ULE, either.

3.2. Energy matching

Energy matching was investigated for each micro-cogeneration concept and control strategy for each climate and energy performance level. The weighted matching index (WMI) was calculated by multiplying the OEF_e, OEF_m, OEF_h and OEF_{th} by the corresponding weight factors listed in Table 8 and summing up the products into a single number, determining the energy match for three preference treatments.

Both the weight values for preference treatment and the criterion of evaluation have been established following the proposal in [12], where the WMI = 0.85 represents a good match.

The results indicate that in the thermal tracking mode, the good match is obtained in the 1960 house in all the examined climates, when the electric car is not present. Provided that all four indices have the equal importance, the WMI = 0.86...0.88 can be obtained, whereas preferring the thermal matching, the WMI = 0.93...0.94.

Table 4

The results of energy analysis in the thermal tracking mode (1960 house).

	η_a [%]	t_{op} [h/y]	$E_{el,-}$ [kW h/y]	$E_{el,+}$ [kW h/y]	$E_{el,on-site}$ [kW h/y]	On-site-% [%]	E_{fuel} [kW h/y]
Helsinki							
SE	76.5	2656	679	291	2969	81	56,989
RSE	83.4	2447	607	442	3041	83	52,503
DTCS	82.8	2471	585	520	3063	84	53,017
Helsinki (e-car)							
SE	77.0	2656	5183	7	3575	41	56,989
RSE	83.9	2447	5045	16	3712	42	52,503
DTCS	83.2	2471	4997	21	3760	43	53,017
Jyväskylä							
SE	76.3	3021	512	413	3136	86	64,833
RSE	83.4	2784	458	720	3190	87	59,734
DTCS	82.8	2811	438	824	3210	88	60,318
Jyväskylä (e-car)							
SE	76.8	3021	4899	16	3859	44	64,833
RSE	83.6	2784	4756	34	4002	46	59,734
DTCS	82.9	2811	4706	41	4052	46	60,318
Sodankylä							
SE	76.7	3601	347	932	3295	90	77,275
RSE	83.9	3333	304	1630	3338	92	71,517
DTCS	83.4	3365	282	1784	3359	92	72,203
Sodankylä (e-car)							
SE	76.7	3601	4549	47	4203	48	77,275
RSE	83.2	3333	4401	91	4351	50	71,517
DTCS	82.5	3365	4341	107	4411	50	72,203

Table 5

The results of energy analysis in the thermal tracking mode (ULE).

	η_a [%]	t_{op} [h/y]	$E_{el,-}$ [kW h/y]	$E_{el,+}$ [kW h/y]	$E_{el,on-site}$ [kW h/y]	On-site-% [%]	E_{fuel} [kW h/y]
Helsinki							
SE	75.9	720	2531	0	1192	32	15,451
RSE	83.2	663	2426	0	1297	35	14,234
DTCS	82.6	670	2387	0	1336	36	14,374
Helsinki (e-car)							
SE	75.9	720	7641	0	1192	13	15,451
RSE	83.2	663	7529	0	1304	15	14,234
DTCS	82.7	670	7487	0	1346	15	14,374
Jyväskylä							
SE	76.4	795	2409	0	1314	35	17,060
RSE	83.7	732	2295	0	1428	38	15,717
DTCS	83.1	740	2254	0	1469	39	15,871
Jyväskylä (e-car)							
SE	76.6	795	7493	0	1341	15	17,060
RSE	83.9	732	7368	0	1465	17	15,717
DTCS	83.4	740	7322	0	1511	17	15,871
Sodankylä							
SE	77.0	953	2179	0	1538	41	20,447
RSE	84.3	878	2055	0	1662	45	18,838
DTCS	83.7	886	2004	0	1713	46	19,022
Sodankylä (e-car)							
SE	77.4	953	7206	0	1621	18	20,447
RSE	84.9	878	7056	0	1771	20	18,838
DTCS	84.4	886	6994	0	1833	21	19,022

Here, the SE micro-cogeneration system receives the highest matching values. If the electric car is present, the WMI = 0.89 is achieved with all the examined micro-cogeneration technologies, when thermal matching is considered more important than electrical matching.

In the ULE, good match is obtained with the RSE technology in Jyväskylä and Sodankylä, provided that the electric car is not present. In the thermal tracking mode, the WMI = 0.89...0.93, when thermal matching is considered more important than electrical matching. The lowest values occur, when the electric car is present. When all the four indices have the equal importance, the WMI = 0.85 can be achieved in Jyväskylä and Sodankylä.

In the electrical tracking mode, the good match is obtained only, when electrical matching is perceived more important than thermal matching. For the 1960 house, WMI = 0.91, when no electric car is present and WMI = 0.86, when an electric car is present. These

values are equal for all the examined climates and technologies. For the ULE house, the corresponding values are 0.89 and 0.87. Differences between the studied micro-cogeneration technologies are minimal, because all the systems are close to each other in terms of their ETTR.

3.3. Impact of energy storages

A parametric study was conducted to evaluate the impact of the energy storage size on the energy matching. For electrical storages (in the thermal tracking mode), the case with no battery and the battery capacities 50, 100, 150 and 200 Ah were examined. Electrical storage efficiencies 60%, 70%, 80%, 90% (reference case) and 100% (no losses) were also explored. DTCS was selected as the reference technology. The results for the 1960 house and the ULE in Helsinki climate are in Fig. 7.

Table 6

The results of energy analysis in the electrical tracking mode (1960 house).

	η_a [%]	t_{op} [h/y]	$E_{th,-}$ [kW h/y]	$E_{th,+}$ [kW h/y]	$E_{th,on-site}$ [kW h/y]	On-site-% [%]	E_{fuel} [kW h/y]
Helsinki							
SE	78.3	2316	16,410	11,355	23,911	59	49,698
RSE	85.7	1949	17,607	9,503	22,713	56	41,827
DTCS	85.2	1907	18,028	8,924	22,293	55	40,926
Helsinki (e-car)							
SE	78.3	2942	20,804	23,998	20,804	60	63,137
RSE	85.7	2707	21,860	22,889	21,860	57	58,099
DTCS	85.2	2681	21,368	22,508	21,368	56	57,523
Jyväskylä							
SE	78.3	2316	20,380	9,734	25,540	56	49,707
RSE	85.7	1949	21,752	8,047	24,169	53	41,827
DTCS	85.2	1907	22,232	7,529	23,688	52	40,926
Jyväskylä (e-car)							
SE	78.3	2942	20,220	19,102	25,701	56	63,137
RSE	85.7	2707	21,454	20,283	24,466	53	58,099
DTCS	85.2	2681	21,875	19,831	24,045	52	57,523
Sodankylä							
SE	78.3	2312	27,025	7,174	28,032	51	49,614
RSE	85.7	1946	28,744	5,815	26,313	48	41,756
DTCS	85.2	1904	29,354	5,461	25,703	47	40,857
Sodankylä (e-car)							
SE	78.3	2973	26,243	16,535	28,814	52	63,788
RSE	85.7	2733	27,731	17,812	27,326	50	58,647
DTCS	85.2	2706	28,209	17,410	26,848	49	58,059

Table 7

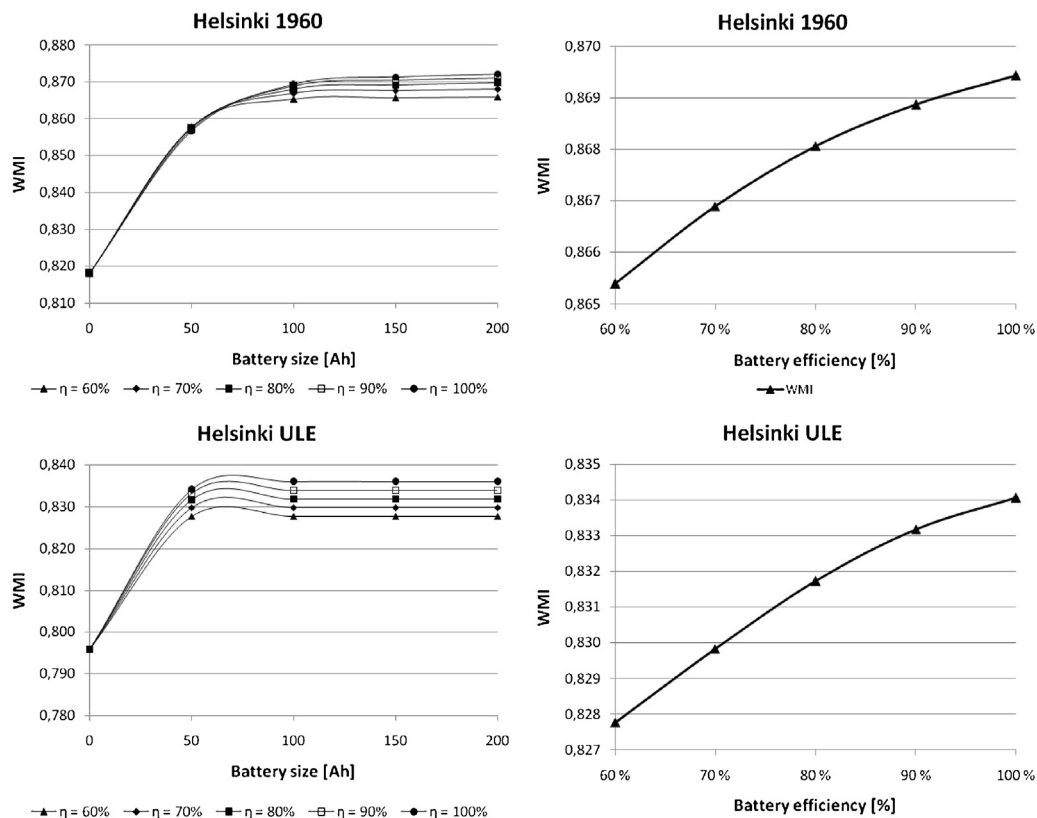
The results of energy analysis in the electrical tracking mode (ULE).

	η_a [%]	t_{op} [h/y]	$E_{th,-}$ [kW h/y]	$E_{th,+}$ [kW h/y]	$E_{th,on-site}$ [kW h/y]	On-site-% [%]	E_{fuel} [kW h/y]
Helsinki							
SE	78.3	2296	1020	25,440	9521	90	49,268
RSE	85.7	1932	1232	22,629	9309	88	41,465
DTCS	85.2	1891	1309	21,715	9232	88	40,572
Helsinki (e-car)							
SE	78.3	2914	1020	34,849	9521	90	62,528
RSE	85.7	2684	1232	35,046	9309	88	57,586
DTCS	85.2	2657	1309	34,262	9232	88	57,021
Jyväskylä							
SE	78.3	2336	1392	25,236	10,335	88	50,128
RSE	85.7	1966	1659	22,427	10,068	86	42,188
DTCS	85.2	1924	1753	21,512	9,975	85	41,280
Jyväskylä (e-car)							
SE	78.3	2954	1392	34,645	10,335	88	63,387
RSE	85.7	2717	1659	34,844	10,068	86	58,310
DTCS	85.2	2690	1753	34,059	9,975	85	57,729
Sodankylä							
SE	78.3	2334	2310	23,643	11,905	84	50,095
RSE	85.7	1965	2646	20,904	11,569	81	42,161
DTCS	85.2	1922	2764	20,015	11,451	81	41,253
Sodankylä (e-car)							
SE	78.3	2987	2310	33,574	11,905	84	64,090
RSE	85.7	2745	2646	33,798	11,569	81	58,901
DTCS	85.2	2717	2764	33,024	11,451	81	58,308

Table 8

Principles for the elicitation weights for calculating the WMI.

Preference treatment	Weights			
	OEF _e	OEM _e	OEF _h	OEM _h
All four indices have the same importance	0.25	0.25	0.25	0.25
Electrical matching is more important than thermal heat matching	0.375	0.375	0.125	0.125
Thermal heat matching is more important than electrical matching	0.125	0.125	0.375	0.375

**Fig. 7.** The impact of battery size and efficiency on the WMI.

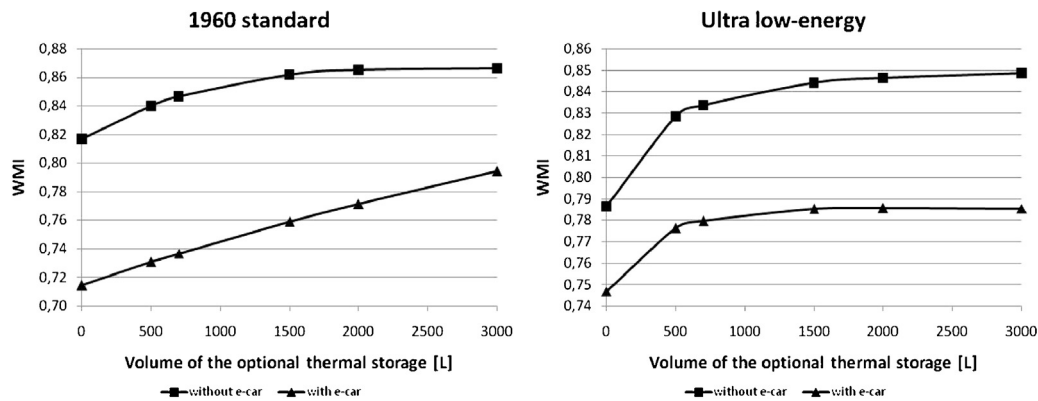


Fig. 8. The impact of external thermal storage size on the WMI.

The data in Fig. 7 indicate that without battery, the WMI exceeds the reference value of 0.75, which was referenced in [12] as a criterion of a good match. It can be also noted that battery sizes more than 100 Ah are not feasible when the aim is to improve the energy matching. Furthermore, Fig. 7 points out that there is only a minor impact of the battery efficiency on the WMI. The above findings are valid for all the examined climatic zones.

The standard boiler system contains a small, in-built thermal storage tank, but the thermal energy match can be further increased by adding a larger extra heat storage to the system. Here, a separate water circulation would be required between the boiler's water tank and the large storage tank. A separate storage tank would also provide with more space to add the heat exchanger for the external thermal grid. For thermal storages (in the electrical tracking mode), the case with no storage and the standard, fully mixed cylindrical tank (sizes 500, 700, 1500, 2000 and 3000 L, effective temperature difference 10 °C) insulated with urethane 100 mm ($U = 0.22 \text{ W/m}^2 \text{ K}$) and additional 5% distribution losses were examined. The results are shown in Fig. 8.

The parametric analysis provides the reader with an idea how the optimal storage size behaves as a function of the thermal energy demand. The better insulated the building is (or the less is its thermal demand due to warmer climate), the smaller storage size is sufficient. The results imply that if the electric car is not present, this arrangement would improve the WMI to the good level, if the storage size is 1500 L or more in the 1960 house. In the ULE, the good level is more difficult to obtain, but increasing the storage size above 1500 L does not provide further improvements to the situation. When the electric car is present, the good WMI cannot be achieved with the given thermal storage options.

4. Conclusions

This paper evaluates the feasibility of conceptual, pellet-fueled micro-cogeneration technologies by way of annual energy balances and weighted energy matching indices (WMI). The concept is based on a commercial 20 kW_{th} wooden-pellet fueled boiler. The study contributes to the research by evaluating the feasibility for both thermal and electrical tracking strategies and examining the option to charge an electric car and to deliver surplus heat to a local thermal grid in detached houses representing two energy performance levels and located in three climatic zones in Finland. The sizing of electrical and thermal storages is also discussed.

In the thermal tracking mode, the net thermal energy demand was completely (100%) fulfilled on-site in all the investigated scenarios. The percentage of on-site electricity was 92% at maximum (1960 house), and 46% (ULE), when the electric car is not present. If the electric car is present, the corresponding percentages were

50% and 21%. Due to its lower efficiency, the Stirling engine provided a performance slightly inferior to that of the RSE and DTCS, whereas the performances of the RSE and DTCS were almost identical. In the electrical tracking mode, the net electrical energy demand was completely (100%) fulfilled on-site, and the micro-cogeneration concepts are capable of generating all the required electricity. When there is an e-car present, some 50% of the annual electrical and thermal demand can be fulfilled in the electrical tracking mode. Due to significant amount of thermal surplus, all the investigated pellet-fueled micro-cogeneration options would require either a connection with a thermal grid or another local thermal management or storage option.

A good energy match (AMI > 0.85) was obtained in the 1960 house in the thermal tracking mode in all the examined climates, when the electric car is not present. When thermal matching is perceived more important than electrical matching, all the cases represented a good match. In the ULE, good match was obtained with the RSE technology in Jyväskylä and Sodankylä, provided that the electric car is not present. In the electrical tracking mode, the good match was obtained only, when electrical matching is perceived more important than thermal matching. Differences between micro-cogeneration technologies were minimal.

The study also pointed out that increasing the battery size to more than 100 Ah is not feasible when the aim is to improve the energy matching. On the other hand, there is only a minor impact of the battery efficiency on the WMI. By adding an extra thermal storage some improvements can be obtained in the energy match. Usually, the storage size of 1500 L is enough, anyway.

The above findings are applicable to cold climates, where space heating significantly impacts the energy consumption of buildings. Specifically, the results can be generalized to the warm summer continental and hemiboreal climate zones (*Dfb* and *Dfc* in the Köppen Climate Classification System), which widely appear in Scandinavian countries, Russia, Canada and the northern part of the US [26]. These results are indicative, however, and experimental research is needed to validate the operation of the conceptual micro-cogeneration systems in realistic conditions. Furthermore, the individual laws and regulations of each country (e.g. the law for pressure vessels) appoint restrictions regarding the implementation of the suggested micro-cogeneration systems.

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